Chapter 24

The MAGS Integrated Modeling System

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Abstract The Mackenzie GEWEX Study (MAGS) integrated modeling system was developed to couple, with full feedback, selected atmospheric and hydrologic models, with the expectation that the imposed consistency will enhance the performance of both models and so mitigate the lack of data for northern basins. As each modeling community moved towards using a common land surface scheme based on the Canadian land surface scheme CLASS, a new mesoscale distributed hydrologic model (WATCLASS) was created, using CLASS for vertical processes and the routing algorithms from WATFLOOD. The version of CLASS used in the atmospheric models was modified to reflect the experience with WATCLASS. Changes were made primarily to the soil water budget and included improvements in the between-layer transfer procedures, the addition of lateral flow, and the enhancement of the treatment of cold soil. The drainage database for the Mackenzie River Basin (MRB) was built from GTOPO-30 digital elevation model and the CCRS-II AVHRR-based landcover classification. Streamflow simulations using the WATCLASS model are compared to measured values for both the MAGS research basins and the major tributaries of the Mackenzie. As well as streamflow, simulated internal state variables from WATCLASS are compared to detailed measurements taken in the research basins. Finally, the water balance of the MRB is examined and the change in storage within the basin is compared to satellite data.

1 Introduction

This chapter presents the integrated modeling system developed for the Mackenzie GEWEX Study (MAGS) to provide a framework that meets the diverse needs of the project, which range from long-term water and energy balances to distributed hour-by-hour feedback for atmospheric models. This system is not the first attempt to model the Mackenzie River Basin (MRB). Special purpose models in support of navigation, hydropower, and pipeline construction have long existed (Fassnacht 1997; Solomon et al. 1977; Soulis and Vincent 1977). It is, however, the first attempt at a general model that covers the watershed in sufficient detail to draw upon local

studies for model development, to produce consistent understanding of the entire Basin, and to enhance the ability to estimate future conditions.

The fundamental goal of the modeling system is to capture the physics of the watershed adequately, especially with respect to cold processes, in order to close, with full feedback, the water and energy budgets for all such applications throughout the MRB, as well as to provide cold-soil algorithms suitable for use in atmospheric models. The modeling system is based on coupling hydrologic and atmospheric models. The key step is using a common land surface scheme to act as an interface between them. The expectation is that by constraining both models to be consistent, each will improve, mitigating the shortage of input data.

The purpose of this chapter is to describe the model development and to demonstrate its application to the water balance of the Mackenzie system. Performance of this coupled model is compared to that of a conventional hydrologic model with respect to hydrographs at locations throughout the watershed. There are no similarly comprehensive observations of the atmospheric fluxes, but the effect of the coupling of the models on local estimates of evapotranspiration is presented.

2 Model Development

The particular challenge in model development was to merge the different atmospheric and hydrologic modeling traditions in such a way that the strengths of both were not compromised while keeping the model agile and robust. The target was to generate a model that met Environment Canada's standards and that was appropriate for use in its operational forecasting and climate simulation systems.

It was clear from the outset that the approach had to involve a combination of both the land surface schemes of the day and the hydrologic models of the day. The land surface schemes, such as SSIB (Goward et al. 2002), BATS (Yang and Dickinson 1996), MOSES (Essery et al. 2001), and CLASS (Verseghy 1991), were developing evaporation schemes that only paid cursory attention to the soil water budget. This was consistent with their emphasis on atmospheric fluxes. Runoff was only of interest in monthly or annual scales as a validation (Avissar and Verstraete 1990; Huang and Liang 2006). On the other hand the hydrology models, VIC (Wood et al. 1992), TOPMODEL (Beven and Kirkby 1979), and WATFLOOD (Kouwen et al. 1993), were all developing sub-grid representations for runoff generation generally involving addressing variations

of landcover and trying to capture the dynamics of variable saturation (Wood 1991). As a result, a merging of the two development paths involved producing a sub-grid representation for the land surface schemes that achieved the hydrology objectives but preserved the interfaces to the atmospheric models.

2.1 Modeling Strategy

Since MAGS was a Canadian initiative, all the models considered were Canadian. The atmospheric models used were the CMC Regional Finite Element (RFE) which was the operational weather prediction model of the day, later replaced by the Global Environmental Model (GEM) (Cote et al. 1998); the CMC Meso-scale Compressible Community (MC2), a research forecast model (Benoit et al. 1997); the CCC-GCM, a general circulation model (Flato et al. 2000); and the CRCM, a regional climate model developed by the University of Quebec for Environment Canada (Caya and Laprise 1999, MacKay et al. 2007). The hydrologic models used were WATFLOOD (Kouwen et al. 1993), SLURP (Kite 1995), and CHRM (Pomeroy et al. 2007). These represented the most physically-based semi-distributed models available during the course of the project.

Both sets of models meet at the land surface where they have a similar need for parameterizations of the vertical water and energy exchanges. In an atmospheric model, a set of such routines is referred to as a land surface scheme. The most developed Canadian scheme was the Canadian Land Surface Scheme (CLASS) (Verseghy 1991) which uses a landcover-based approach. WATFLOOD has a simple vertical water and energy budget and a very well developed routing scheme. There is enough similarity in architecture that makes it practical to use CLASS as a link between the atmospheric and hydrologic models.

The modeling strategy aimed at establishing CLASS as a link between the two sets of models (Fig. 1). Each column in the figure represents a stage of model development that was given its own level number. The first step was to run the atmospheric models separately and use their output to force WATFLOOD (Level 0). The next step was to add a common version of CLASS to each model independently. This involved simply revising the Environment Canada physics libraries for the atmospheric models (Level 1) but for hydrologic modeling it required the creation of an entirely new model called WATCLASS (Level 2). The final step involved using CLASS as a bridge between models, providing complete coupling (Level 3). The assumption was that the two-way feedbacks would provide high

quality input and that the requirement for matching boundary conditions would increase the predictive power of the coupled model. During the course of MAGS, Levels 0, 1 and 2 were achieved and the framework for progressing with Level 3 was established.

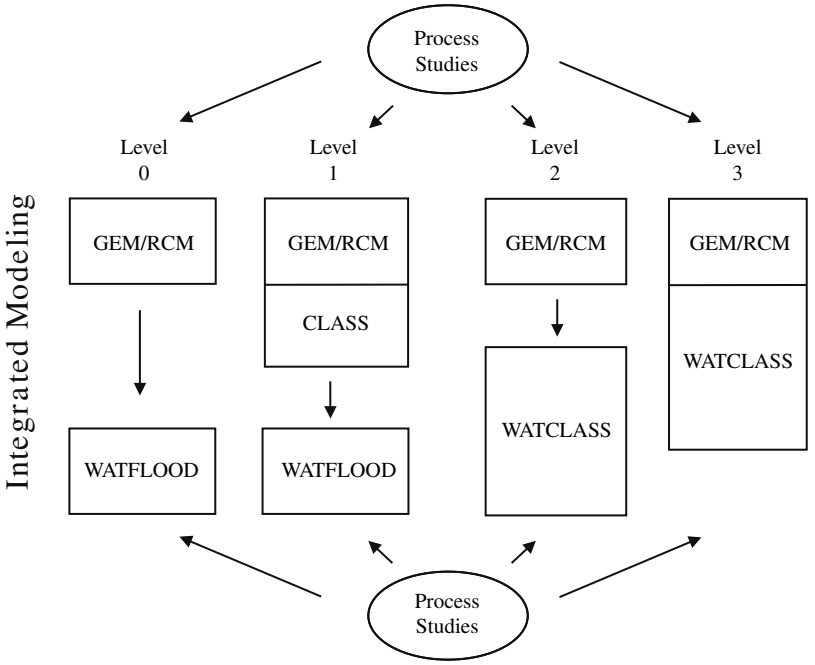

Fig. 1. Mackenzie GEWEX Study (MAGS) modeling strategy

2.2 Development of WATCLASS

Several objectives determined the approach to the design of WATCLASS. The first was to minimize the changes to the basic CLASS architecture and the second was to introduce as much physics as practical, especially in the soil water budget, but with as few calibration coefficients as possible because of the limited data available. As well, CLASS is most interested in atmospheric fluxes and thus has a detailed energy balance and all state variables are intrinsic including soil moisture. WATFLOOD focuses on streamflow and thus has a rudimentary but robust treatment of the energy balance and all state variables are bulk values.

2.2.1 Sub-grid Modeling

While both models make use of the distribution of landcover for sub-grid process modeling, CLASS uses a properties-summed-by-area single landscape unit approach and WATFLOOD uses a fluxes-summed-by-area multiple hydrologic unit approach called the Group Response Unit (GRU) approach (Kouwen et al. 1993). CLASS originally allowed one landscape category per grid cell. This is similar to the hydrologic response unit (HRU) approach (Wood 1991) except that, although a single land cover element is used to represent a grid, its properties are a blend of a generic set of landscape types. For example, a unique albedo was determined for each grid using an area-weighted sum of the albedos for the component tree types. Furthermore, there was limited provision for runoff in CLASS resulting in excess surface ponding and drainage from the soil column being discarded.

WATCLASS uses a set of generic grouped response units that are more sophisticated than in the original GRU approach. They can represent any landscape unit for which the hydrologic response can be defined, such as peat plateau or glacier. The most common, however, is the classical hillslope representation. All landscape units regardless of type are assigned a local slope to provide a gradient for lateral flow. Thus the modeling could be said to be using Modeling by Aggregating Sloped tiles or the MAGS tile approach.

There is a potential for improvement to the within-grid runoff collecting algorithms. While CLASS successfully produces long term water balances partly because of its careful treatment of the canopy processes, it is not as successful in short term runoff generation, resulting in poor soil water balances and poor hydrographs. The MAGS tile approach improves the local water balances and the WATFLOOD grid-to-grid routing algorithm converts runoff to streamflow at points of interest. However, WATCLASS within-grid routing still uses the WATFLOOD assumption that the subgrid runoff is immediately transferred to the point on the main channel where it enters the grid element. The extra travel time spent in the main channel is to account for the subgrid collection time. This treatment is adequate in certain situations such as mixed landcover in temperate zones where a channel network is the major collection mechanism. This is not true in the North. For example, in wetland areas flow occurs in wide and slow moving fens (Quinton and Hayashi 2007) and in Shield areas flow is significantly delayed because of lake storage (Woo and Mielko 2007).

2.2.2 Soil Water Movement

The attention paid to the water movement within-elements was rudimentary in the original version of CLASS, in contrast to the well developed treatment of vegetation. Changes were made to bring the soil water budget to the same level. Briefly, slope was added to the CLASS soil element to provide the gradient for lateral flow (Fig. 2); surface flow was calculated using Manning's equation, and interflow using a control-volume parameterization of Richard's equation (Soulis et al. 2000). Drainage (recharge) was calculated as before using Darcy's law but was transferred to a grid scale linear reservoir to simulate local ground water. Cold-soil parameterizations were enhanced as follows. Effective saturation and saturation conductivity were adjusted to reflect ice content. Conductivity was adjusted for temperature effects and a partial snowcover algorithm was introduced. Other parameterizations included adjustment for the effect of temperature on viscosity and a provision for a separate depth at which 100% snowcover is assumed (D_{100}) for old snow and fresh snow. The most significant changes are presented briefly in the following subsections.

2.2.3 Lateral Flow

Interflow is a runoff mechanism of particular importance in northern regions mainly because of the presence of ice. Ground ice in seasonal frost and in permafrost blocks the vertical pathways in favor of near-surface lateral flow. No such provision was provided for in the original CLASS.

There are no well developed parameterizations for lateral flow. However, there is considerable modeling experience that typically uses an exponential relationship between near-surface storage and outflow. These parameters are typically determined by calibration, which is generally not practical for regional modeling of systems like the Mackenzie. The objective was, therefore, to develop a set of equations that describe these mechanisms rigorously, relying only on the material properties and the bulk state variables of soil moisture and temperature. WATCLASS uses essentially the same physics for vertical flow as the original CLASS but treats the soil column as a sloping aquifer. This follows a kinematic wave approach with modifications to reflect the extreme variation of soil properties with depth of northern soils. An analytic solution to Richard's equation is used to approximate the expected value of the soil moisture distribution for a given average soil moisture. The boundary values of soil moisture are used to define the interflow. The parameterization, shown in Fig. 3, is approximated by

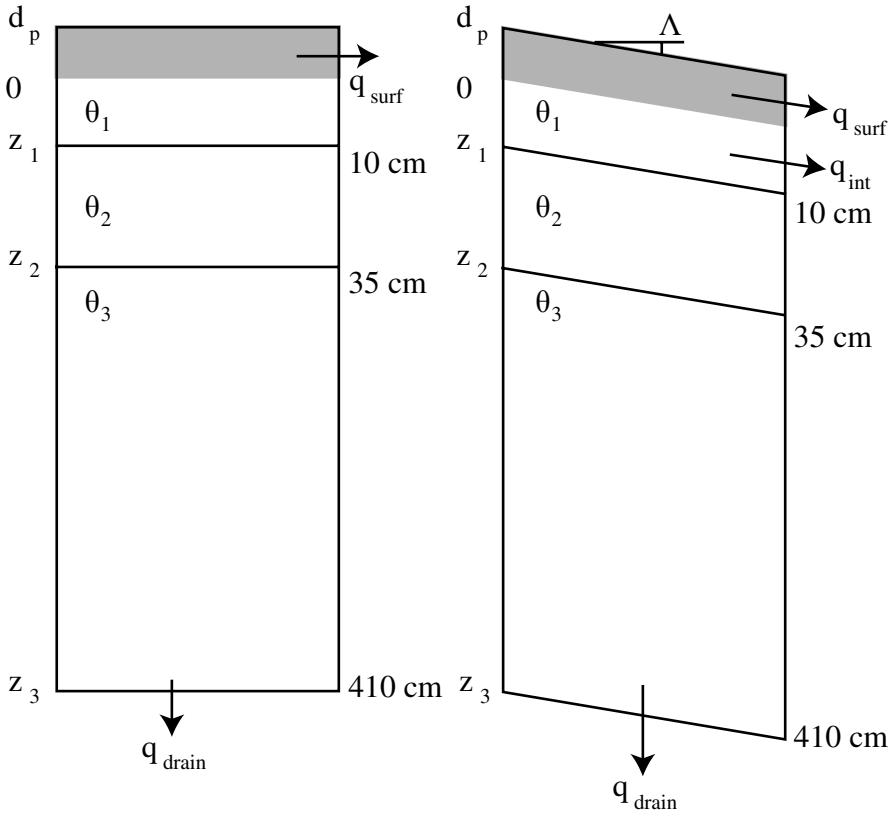

Fig. 2. Modified CLASS sloped soil algorithm

$$q_{INT} = 2D_D \cdot K_0(\theta_S) \cdot S^f \cdot \varepsilon H \cdot \Lambda_I \tag{1}$$

where S is effective saturation, H is aquifer thickness, Λ_I is aquifer slope, D_D is drainage density, f is a coefficient, and ε is an aquifer efficiency that ranges from 0 to 1, given by

$$\varepsilon = (1 - e^{-\lambda H}) / \lambda H \tag{2}$$

where λ is a conductivity decay coefficient (Soulis et al. 2000). The values for f depend upon λH and other soil properties and typically range from 1 to 4, which is consistent with modeling experience. Prior to the introduction of the interflow algorithm, the model predicts a period of saturated flow. This is because the seepage face remains saturated for some time following the start of the recession.

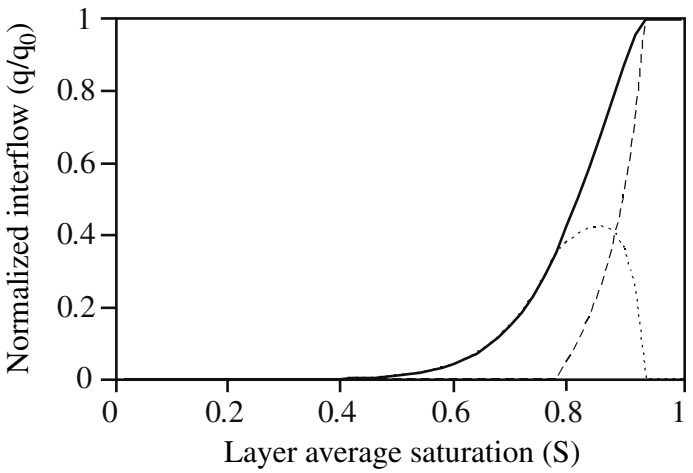

Fig. 3. Interflow characteristic curve example (c = 8, K′ = 0.67,) (solid line). The short dashed curve is for unsaturated flow from the seepage face. The long dashed curve is for saturated flow from the seepage face

2.2.4 Drainage

The same approach that was used to model interflow was applied to drainage. The original CLASS used Campbell's equation (Verseghy 1991) and assumed Darcian flow for flow from the bottom of the soil column. Consequently, due to the sensitivity of drainage to soil moisture, the drainage showed little variation. As soon as the third soil layer dropped below saturation the drainage would decline rapidly; therefore the only option was to set the drainage parameters such that the drainage was virtually a constant value. The WATCLASS approach is flexible enough that saturated flow continues until the soil moisture drops below the field capacity, after which flow declines quickly. Where this transition occurs depends upon K', which is the ratio of horizontal conductivity at the bottom of the layer divided by horizontal conductivity at the top of the layer (Fig. 4).

2.2.5 Between-layer Conductivity

The between-layer-conductivity calculation is the most important change related to estimating soil properties. The original implicit finite difference scheme used an arithmetic mean of layer properties at the boundaries that resulted in chronic supersaturation of the receiving layers. Furthermore, it made the model extremely difficult to calibrate because the layer with the the reverse. In the current scheme, flow at the boundaries is controlled by

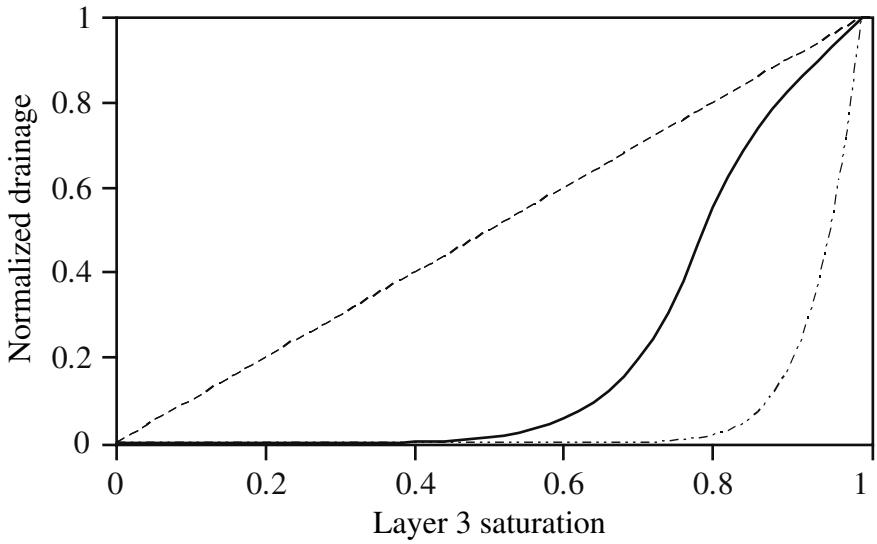

Fig. 4. Drainage characteristic curve example (c = 8, K' = 0.67) (solid line). The dashed straight line is for linear recession curve. The dashed curve line is for matrix flow

the harmonic mean of the conductivity of the adjacent layers (Fig. 5). This is a common practice in ground water models (McDonald and Harbaugh 1988) as it ensures equal fluxes at the boundary. Furthermore, the boundary conductivity is dominated by the lesser of the two values and thus limits the flow in and out of the final layers to physically plausible values.

2.2.6 Cold-soil Processes

The original CLASS had limited sensitivity to ice conditions in the soil. Ice content was assumed to reduce pore space but other soil properties did not change. In WATCLASS, conductivity and porosity were both adjusted to reflect the presence of ice. Porosity was allowed to change when ice was formed to simulate frost heave. Effective porosity is calculated as follows:

$$\phi_{effective} = \max\left(\theta_{liq} - \theta_{\min}, \phi - \theta_{ice} - \theta_{\min}, 0\right) \tag{3}$$

where θ_{liq}, θ_{min}, and θ_{ice} are volumetric content of liquid water, hydroscopic water, and ice, respectively. Similarly, the degree of saturation is adjusted for ice content (Fig. 6). When ice is present it is considered to be part of the soil matrix that reduces the pore space, thereby increasing effective

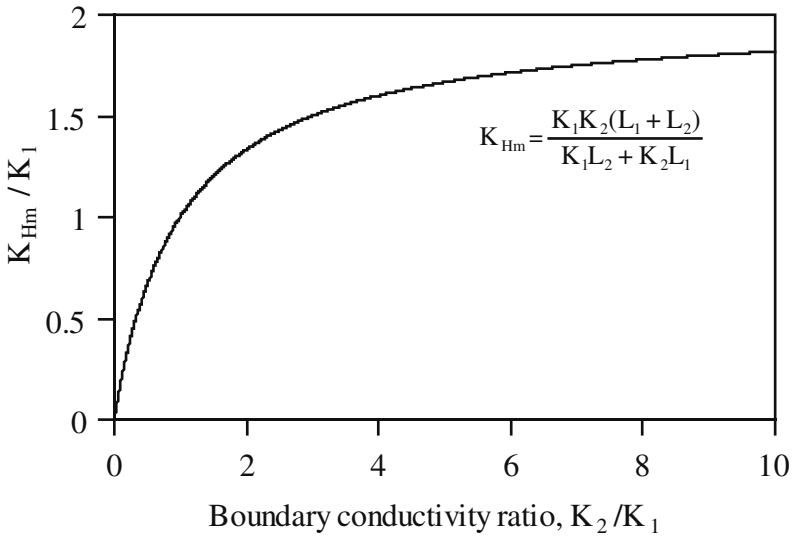

Fig. 5. Normalized harmonic mean. For uniform soil and an evenly spaced grid $K_{Hm} = K$, for $K_2 >> K_1$, $K_{Hm} = 2*K_1$. Dominated by the smaller of K_1 and K_2, K_{Hm} ensures consistent fluxes across the layer boundaries

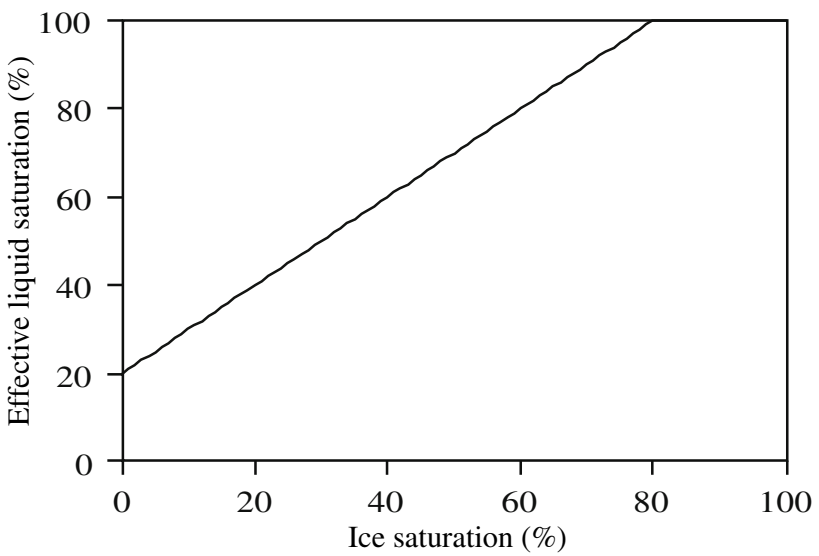

Fig. 6. Effective saturation vs. ice content (ice free liquid content of 20%). When ice is present it is considered to be part of the soil matrix. Super-saturation is permitted to allow for the expansion of ice

saturation, as well as reducing pore size and connectivity which decreases the saturated conductivity.

Conductivity is adjusted by a modified form of the impedance factor (Zhao and Gray 1997):

$$k_{ice} = k_0 \cdot \left(1 - f_{ice}\right)^d \tag{4}$$

where k_0 is the saturated hydraulic conductivity with no ice present, f_{ice} is the ice fraction, and d is an exponent (Fig. 7). Horizontal flow is restricted by reducing the thickness of the transmitting layer, which is directly related to the ice fraction. Thus d has the value of 1. Vertical movement is through the connected pores in the frozen soil. Assuming that these pathways lose cross-section more than length and that laminar flow dominates, d has a value of 2.

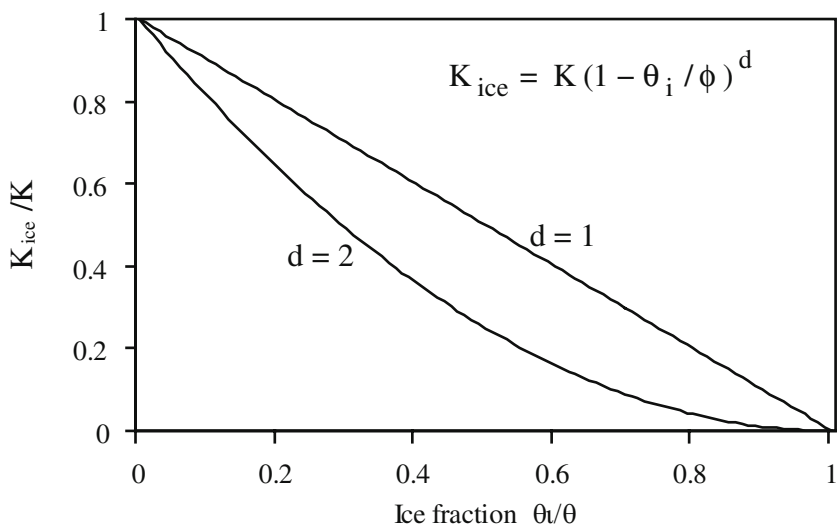

Fig. 7. Ice impedance factor vs. ice fraction. For horizontal flow, most reduction in flow is due to the reduction in the cross section of the layer, thus d =1. For vertical movement, the flow must pass through the frozen layer. Assuming that ice preferentially reduces the pore cross-section and that the flow conditions are laminar, d = 2

CLASS accounts for the aging of the snow pack through changing the values for snow albedo and snow density (Verseghy 1991). WATCLASS extended this to adjust for the effect of partial snow cover on a snow covered area as shown in Fig. 8. Separate values for the depth at which 100%

snowcover is assumed (D_{100}) were applied depending on the age of the snow pack.

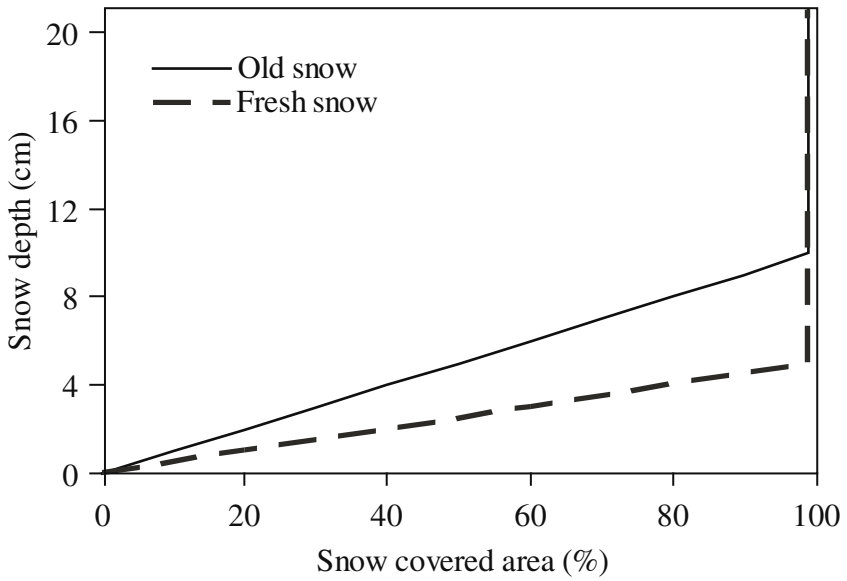

Fig. 8. D_{100} for fresh snow and old snow (Davison 2004)

3 The MAGS Modeling System

Modeling the MRB system is essentially keeping track of the components of the energy and water budgets throughout space and time. Two important preliminary steps are selecting a space and time resolution, and populating the corresponding databases.

3.1 Space and Time Resolution

An integral component of the WATFLOOD/WATCLASS modeling framework is the segmentation of a basin into gridded computational units. Unlike the atmosphere, when the land-surface is subdivided the gridding process requires locations to be explicitly considered in order to maintain the proper drainage network and sub-grid properties. This segmentation process condenses the data to a format that preserves as much of the input information as possible, while greatly reducing the program memory re-

quirements (Kouwen et al. 1993). The choice of resolutions in this study reflected the requirements of both atmospheric and hydrologic modeling.

A one-hour time step was selected for the temporal resolution. Time steps for atmospheric modeling are typically 30 minutes to one hour, as dictated by the need to resolve diurnal cycles. Hydrologic phenomena evolve more slowly than atmospheric phenomena and longer time steps are acceptable, but one hour is often used for convenience especially in distributed models (Kouwen et al. 2005). In terms of spatial resolution, MAGS was committed by GEWEX to establish monthly balances at a scale of 100 km (Szeto et al. 2007). It is good modeling practice to use resolutions that are approximately one order of magnitude less than the target resolution, which suggested a grid spacing of 3 to 30 km.

Because of the heterogeneity of the Earth's surface, hydrologic processes occur over small domains, often much less than 1 km. Bookkeeping becomes impractical at this resolution and a grid must be imposed that, in effect, determines a separation between explicit modeling and sub-grid distribution-based modeling. Sub-grid travel time considerations dictate that the area of one grid should be no more than approximately 4% of the area of the smallest tributary of interest. Channel routing considerations limit grid spacing to no more than 50 km. Ten kilometers is about the low end of the scale at which atmospheric phenomena can be resolved and it is about the size at which landscape units are detectable by the boundary layer. Grid size for global atmospheric models at the outset of MAGS was about 250 km but decreased rapidly as computer technology improved. A 20 km grid was selected after consideration of the size of the domain, the target resolutions, model considerations, and the available data sources.

3.2 Input Databases

The Global 30 Arc-Second Elevation Data Set (GTOPO-30), available from the US Geological Survey (USGS 1997) and distributed by the EROS Data Center (EDC) Land Processes DAAC, provides 30 arc-second elevation data globally. This is equivalent to a spatial resolution of approximately 900 m in the Mackenzie region. For this study, digital elevation data for the Mackenzie Basin were extracted from GTOPO-30 (Fig. 1 in Trischenko et al. 2007) and verified using detailed local DEMs at Fort Simpson and Wolf Creek.

During the life span of MAGS, several AVHRR-based 1 km landcover classifications became available (Hansen et al. 2000; Steyaert and Knapp 1999). Six AVHRR-based datasets, four global and two Canadian, were

evaluated using LANDSAT images at the three MAGS research basins (Pietroniro and Soulis 2000). The Canadian CCRS-II classification (Cihlar and Beaubien 1998) performed the best but still only achieved 30% accuracy on a pixel-by-pixel basis and minor land classes were often missed altogether. However, when averaged over the 20 km grid used in this study, the error in landcover fractions was typically within 5% absolute error.

The CCRS-II product contained 31 land cover classes. However, a number of these classes can be combined for atmospheric and hydrologic investigations (Fig. 1 in Trischenko et al. 2007). For the current generation of hydrologic models, differences in the hydrologic response between similar land classes (e.g., mixed intermediate uniform forest and mixed intermediate heterogeneous forest) cannot be determined without detailed field investigations, and parameter sets that quantify hydrologic response are only available for broad land cover categories. Thus, the 31 land cover classes of the original classification were aggregated to seven classes, viz., water, wetland, agricultural, tundra, coniferous forest, mixed forest, and glacier.

3.3 Drainage Database

WATFLOOD and WATCLASS require a basin to be properly divided into segments or grids, with each grid square containing information on the following characteristics: river elevation, drainage area, drainage direction, river classification, contour density, routing reach number, and land cover class (see Kouwen et al. 1993 for detailed description of the characteristics). These characteristics are referred to as the drainage database. The drainage database was created using the Topographic Parameterization (TOPAZ) (Martz et al. 2007) and the Waterloo Mapping Program (WATMAP) (Seglenieks et al. 2004). These programs use the topographic and land cover databases to derive the drainage database. An example of one of the characteristics from the drainage database is the drainage network (Fig. 2 in MacKay et al. 2007).

4 Model Evaluation

Streamflow simulated by the WATCLASS model for several research basins and for the Mackenzie River and its major tributaries were compared to measure values. In addition, certain state variables were examined to evaluate model performance. For streamflow comparison, we used the

Nash coefficient (Nash and Sutcliffe 1970) which is a widely accepted measure of goodness of fit. This coefficient has a range from negative infinity to 1.0, with values less than 0.0 indicating that the observed mean is a better predictor than the model while a value of 1.0 shows a perfect fit for the model (Legates and McCabe 1999).

4.1 Streamflow – Research Basins

The Smoky River, a sub-watershed of the Peace system was used for preliminary testing of WATCLASS. This river drains an area of 3840 km^2 at the foothills of the Rocky Mountain northwest of Edmonton. The basin is largely covered by alpine forest. A comparison of the streamflow simulation results using the original version of CLASS 2.6 to those using WATCLASS with its enhanced hydrology shows the marked improvement when using WATCLASS (Fig. 9). Typically values of the Nash coefficient were less than zero for the original version of CLASS and 0.86 for WATCLASS. Annual runoff errors were in the range of 10 mm per year, about 5% of the annual amount.

Two MAGS research watersheds were also used for testing and validation of WATCLASS. The Wolf Creek research basin is located in the headwaters of the Yukon River approximately 15 km south of Whitehorse, Yukon Territory. It has a drainage area of 195 km^2 and consists mainly of small open spruce forest and low-lying shrubland with some areas of boreal forest and alpine tundra (Martz et al. 2007). Sample results for Wolf Creek streamflow of 1996–2001 show that the Nash coefficient was 0.68 (Fig. 10a). The missed peak flows are consistent with known beaver dam breaks or the clearing of ice from lake outlet (cf., Hicks and Beltaos 2007), both of which are not currently modeled in WATCLASS. Another research basin (area 57 km^2), that of theTrail Valley Creek, is located approximately 50 km northwest of Inuvik, NWT (Fig. 1 in Marsh et al. 2007), in the zone of continuous permafrost at the fringe of forest–tundra transition. The stream occupies an abandoned glacial meltwater channel carved into a plateau. Sample result for Trail Valley Creek (Fig. 10b) indicates a good fit between the simulated and measured streamflow of 1996, with a Nash coefficient of 0.89.

4.2 Streamflow – Mackenzie River Basin (MRB)

The next step in the evaluation of WATCLASS was its comparison to WATFLOOD over the entire MRB for a 10 year period (1994–2003). It

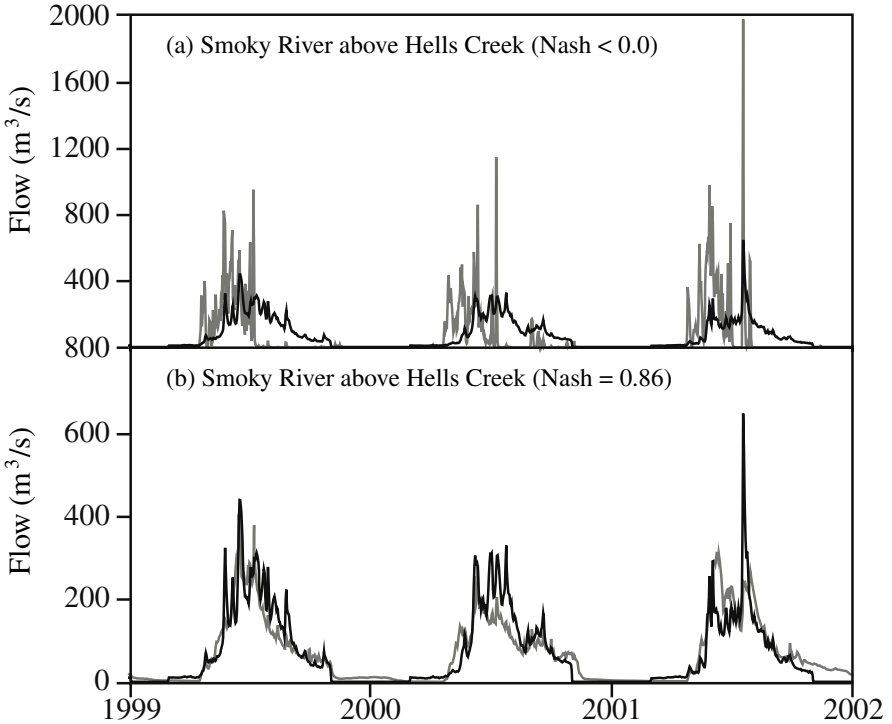

Fig. 9. Comparison of WATCLASS using (a) original and (b) enhanced hydrology, and applied to Smoky River above Hells Creek. (black/thin line is measured, grey/thick line is simulated)

should be noted that WATFLOOD has been used for over three decades and has been calibrated for basins around the world. In contrast, WATCLASS has only been in development during the 10 years of this study and has only been applied to a small number of basins. Thus the land cover parameters are much more developed for WATFLOOD and should be expected to make better simulations of streamflow.

During the course of MAGS, six sets of forcing data became available. The first set consisted of output from the Environment Canada operational weather forecast model. At the beginning of the project this was the only gridded data source available over the entire basin that contained all the necessary fields to run both WATFLOOD and WATCLASS. From January 1994 to June 1998 the Environment Canada operational weather forecast model was the Regional Finite Model (RFE) (Benoit et al. 1989) and since July 1998 it has been the Global Environmental Multiscale (GEM) model (Cote et al. 1998). The RFE and GEM models have problems cor-

rectly simulating the precipitation. To compensate for this, the simulated precipitation from the RFE/GEM models was adjusted using a set of measured monthly precipitation data (Louie et al. 2002) that was available between 1994 and 2000. Only the precipitation data were corrected and all other fields were left unchanged. This data set is referred to as the adjusted RFE/GEM data.

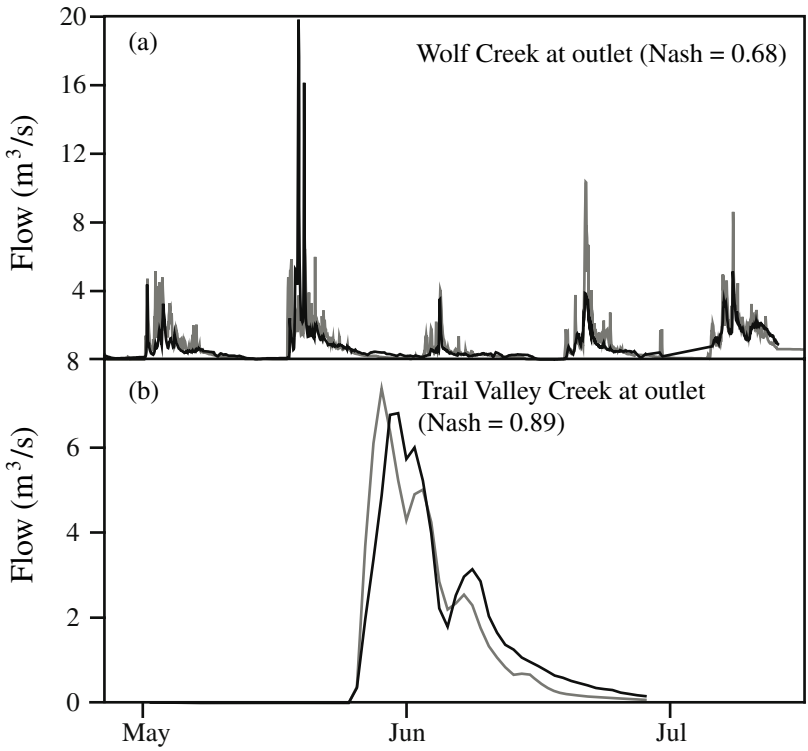

Fig. 10. WATCLASS simulation for (a) Wolf Creek basin outlet, and (b) Trail Valley Creek in 1996 (black/thin line is measured, grey/thick line is simulated)

Both WATFLOOD and WATCLASS were calibrated on the streamflow gauge located on the Liard River at Fort Liard for the years 1994–96 using the RFE/GEM data. This location was chosen because it is the largest unregulated watershed within the MRB. The hydrologic parameters for both models were adjusted to minimize the differences between the measured and simulated flows for the chosen streamflow gauge. These parameters were then used for simulations on other areas of the watershed.

During the latter part of the project other data sets became available: observed data from Environment Canada, NCEP/NCAR reanalysis 1 data (Kalnay et al. 1996), ECMWF reanalysis ERA-40 data (Uppala et al. 2005), and CRCM4.0c data (MacKay et al. 2006). These datasets were used to simulate hydrographs using the calibration parameters sets derived using the RFE/GEM data.

Figure 11 presents the hydrographs of the measured and simulated streamflow at the four major gauging sites in the MRB using the adjusted RFE/GEM data. The Nash values associated with the simulations using the other forcing datasets are also presented (Table 1). Note that the observed data from Environment Canada does not contain enough information to run WATCLASS and thus only WATFLOOD results are available using this dataset.

The simulations using the raw RFE/GEM data and the adjusted RFE/GEM data show that greater precipitation of the adjusted data led to better simulated flows (higher Nash values). The observed forcing dataset creates a streamflow simulation that matches well with the measured values, producing the highest Nash values for the WATFLOOD model. The ERA-40 forcing dataset results in a simulation with good overall fit and Nash values approaching 0.80. Both the NCEP/NCAR forcing data and the CRCM 4.0c forcing data contain an excess of precipitation, causing simulated streamflows that are consistently higher than the measured values and thus low Nash values. Overall, the Nash values for WATFLOOD and WATCLASS simulation were comparable.

4.3 State Variables – Research Basins

It is important to evaluate hydrologic models based not only on streamflow results, but also on several major internal variables. While hydrograph comparisons are very important, streamflow is the aggregation of many different hydrologic processes, and it is possible to incorrectly simulate internal variables that would cancel out and yet produce correct streamflow simulations. For example, an overestimation of snowmelt runoff could be compensated by an overestimation of evaportranspiration, resulting in correct simulated streamflows but for the wrong reasons. If, however, internal variables can be shown to compare well to measured values, then it will increase confidence in the streamflow simulations. It is also important to compare the model results to independent sources, as model to model comparisons are inherently risky.

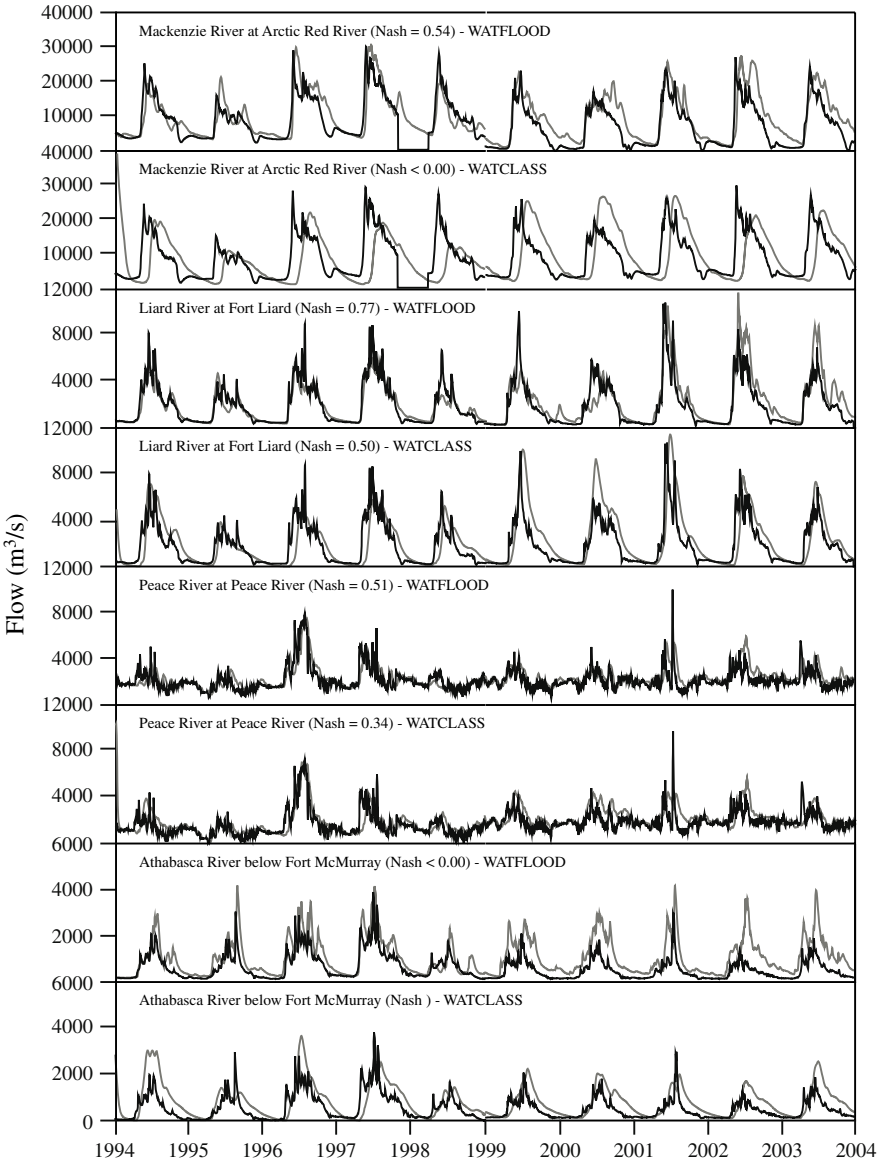

Fig. 11. WATFLOOD (left) and WATCLASS (right) results on the Mackenzie Rive Basin using RFE/GEM adjusted forcing data (black/thin line is measured, grey/thick line is simulated)

Table 1. Nash coefficient for simulations at major streamflow gauges of the Mackenzie River Basin using different forcing data sets for (a) WATFLOOD and (b) WATCLASS

Streamflow gauge	Forcing data set					
	Obs.	GEM	GEM adj.	ERA-40	NCEP	CRCM
(a) WATFLOOD						
Mackenzie at Arctic Red R.	0.67	0.16	0.54	0.76	<0.0	0.11
Liard R. at Fort Liard	0.88	0.3	0.77	0.79	<0.0	<0.0
Peace R. at Peace River	0.58	0.21	0.51	0.62	<0.0	<0.0
Athabasca R. at F. McMurray	<0.0	<0.0	<0.0	<0.0	<0.0	<0.0
(b) WATCLASS						
Mackenzie at Arctic Red R.		<0.0	<0.0	0.63	<0.0	<0.0
Liard R. at Fort Liard		0.51	0.5	0.8	<0.0	<0.0
Peace R. at Peace River		0.11	0.37	0.77	<0.0	<0.0
Athabasca R. at F. McMurray		<0.0	<0.0	0.31	<0.0	<0.0

The Wolf Creek research basin, intensely monitored during the MAGS project, offers high quality dataset for direct comparison of many internal variables. An example is provided in Fig. 12 that compares the simulated with the measured values of snow water equivalent, soil moisture and temperature in the upper soil layer. In general, the simulated and the measured values are in good agreement. This is a sampling of the internal state variables that can be examined when using advanced distributed hydrologic models such as WATFLOOD and WATCLASS. Further model development will require the comparison of an expanded set of internal variables to detailed field measurements.

4.4 Comparison with GRACE Results

During the last few years of MAGS, a remote sensing technique became available that allowed for a direct calculation of storage within the Basin. Previously, remote sensing tools that estimated basin wetness used surrogates such as snow covered area or extent of surface water. The Gravity Recovery and Climate Experiment (GRACE) (Tapley et al. 2004) produces integrated geopotential anomalies that relate directly to stored water. Figure 13 compares the simulated storage in the MRB using the WATFLOOD and WATCLASS models to the storage calculated using the GRACE satellites. Although the two datasets only intersect for two years of the study, it is encouraging to see the general agreement between two very different methods of calculating basin storage.

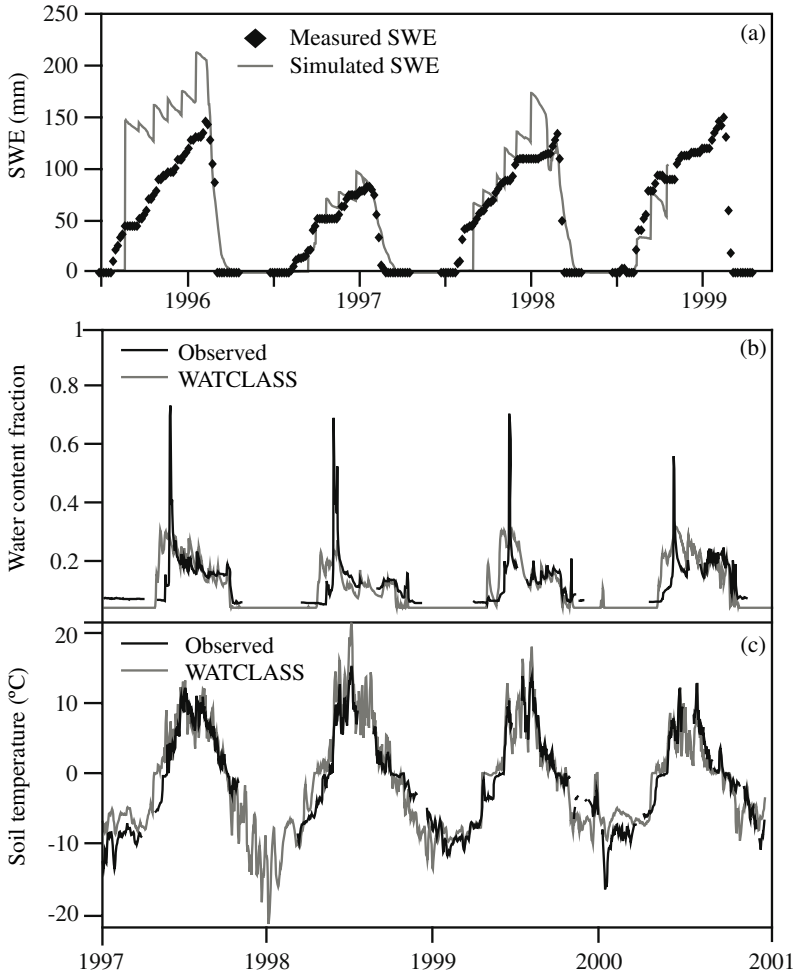

Fig. 12. Comparison of selected internal variables simulated and measured at the Wolf Creek research basin: (a) snow water equivalent, (b) water content fraction in the upper soil layer, and (c) soil temperature in the upper soil layer

5 Application

5.1 Water Budget – Mackenzie River Basin

The ability of WATFLOOD and WATCLASS in closing the water budget for the MRB was examined by calculating the evaporation and runoff for each grid square of the Basin. Combining this information with the pre-

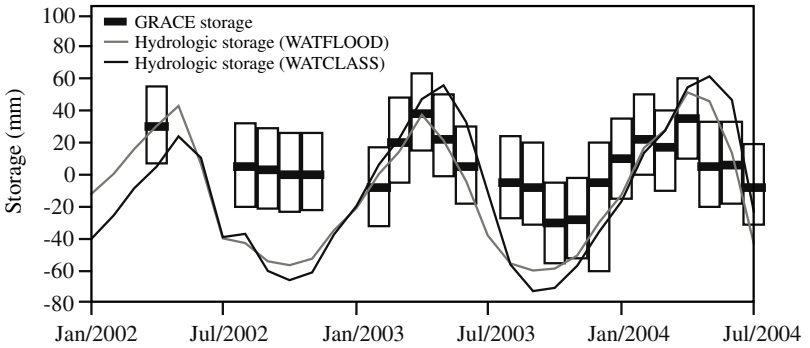

Fig. 13. Terrestrial water storage anomalies in the Mackenzie River Basin using GRACE and WATFLOOD (adapted after Yirdaw)

cipitation from the forcing dataset allowed the storage to be derived for each grid square during each time step. In many studies, it is assumed that this storage term will sum to zero over the course of an annual cycle. However, this does not allow for the basin to have a wetting or drying cycle that lasts over several years.

Water budgets for the MRB using the adjusted RFE/GEM forcing data (Table 2) suggest that the Basin was gaining moisture during 1994–2004, though the average change of storage over the 10 years was less than 1% of the average precipitation and this magnitude is within the error in the measurements. Interestingly, the annual variation in basin storage is much larger in the WATCLASS model, and the amount of annual variation in storage is comparable to that found in a study of the Bityug River in Russia (Chebotarev 1966).

In general, the WATCLASS model calculates more evaporation and therefore less runoff than the WATFLOOD model (Table 2). The term precipitation minus evaportranspiration (P–E) is also shown so that it can be compared to the atmospheric P–E commonly provided by atmospheric studies. In particular, atmospheric P–E was calculated for the MRB based both on GEM output (Strong et al. 2002) and ERA-40 (Schuster 2007) output. These were compared to the hydrological P–E simulated with WATCLASS (Fig. 14) and the results show good agreement.

Table 2. Mackenzie River Basin water budget results from (a) WATFLOOD, and (b) WATCLASS, using RFE/GEM adjusted forcing data (all values in mm)

Water Year	Water budget results				
	Precipitation	Evaporation	Hydrologic P-E	Local runoff	Δ Storage
(a) WATFLOOD					
1994-95	370.3	242.9	127.4	130.7	-3.3
1995-96	468.6	259.4	209.2	186.5	22.7
1996-97	479.0	260.3	218.7	217.1	1.6
1997-98	372.1	261.4	110.8	131.5	-20.7
1998-99	432.6	220.8	211.8	195.3	16.4
1999-2000	446.8	231.4	215.5	209.5	5.9
2000-01	422.8	212.9	209.9	219.5	-9.6
2001-02	463.5	209.0	254.4	245.3	9.2
2002-03	457.7	222.3	235.4	237.5	-2.2
2003-04	461.0	216.7	244.3	240.9	3.5
Average	437.4	233.7	203.7	201.4	2.4
(b) WATCLASS					
1994-95	369.8	253.4	116.4	100.7	15.7
1995-96	467.5	255.6	211.9	107.3	104.6
1996-97	476.9	258.0	218.8	166.6	52.3
1997-98	372.3	274.2	98.0	141.0	-42.9
1998-99	431.1	238.2	193.4	153.6	39.8
1999-2000	443.4	234.6	208.8	182.6	26.1
2000-01	423.1	229.3	193.8	267.9	-74.2
2001-02	464.1	234.3	229.7	266.9	-37.2
2002-03	457.6	240.1	217.6	275.3	-57.7
2003-04	496.6	241.3	255.3	244.5	10.8
Average	440.3	245.9	194.4	190.6	3.7

5.2 Estimation of Changes in Evapotranspiration

One of the project goals was to assess the impact of integrated modeling on the atmospheric fluxes, particularly latent heat. BOREAS, a large scale international interdisciplinary experiment in the northern boreal forests of Canada between 1994 and 1996 (Sellers et al. 1997), offered a BOREAS Northern Study Area (NSA) dataset suitable for testing the sensitivity of evapotranspiration using WATCLASS. Table 3 summarizes the results for the BOREAS. For these, WATCLASS was run in three modes on selected points in the NSA: the first simulations case uses CLASS with vertical processes only, the second case integrated sub-grid lateral flow was intro-

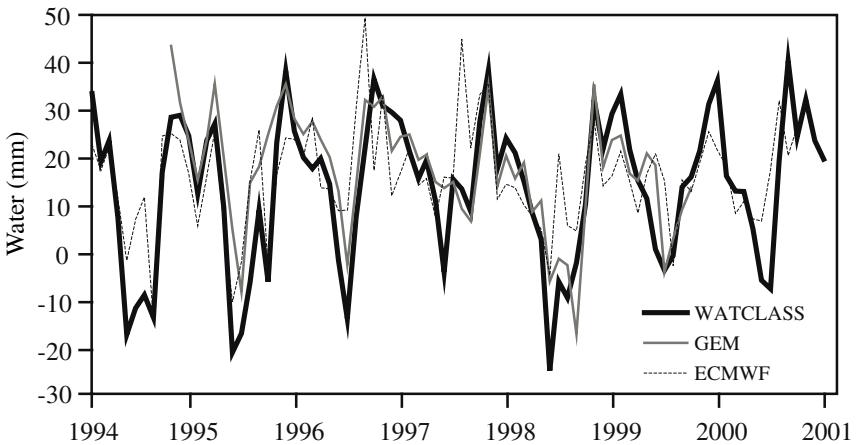

Fig. 14. Comparison of hydrological P–E and atmospheric P–E

Table 3. Evapotranspiration for the BOREAS study area using different WATCLASS modes. Entries are seasonal average for 1994–96 for selected points in the Northern Study Area

	No sub-grid lateral flow, no enhanced cold-soil physics	Sub-grid lateral flow, no enhanced cold-soil physics		Sub-grid lateral flow, enhanced cold-soil physics	
	[mm]	[mm]	[% difference]	[mm]	[% difference]
(a) Dry forest					
Spring	77.1	91.9	19.1	168.9	119.0
Summer	155.6	133.5	-14.3	202.9	30.4
Fall	10.3	2.6	-74.9	24.4	137.0
Annual	243.2	229.1	-5.8	400.4	64.7
(b) Wet forest					
Spring	114.5	101.7	-11.2	148.9	30.1
Summer	148.4	123.5	-16.8	155.6	4.8
Fall	9.1	-2.7	-130.0	13.2	44.9
Annual	274.3	223.6	-18.5	320.6	16.9
(c) Wetland					
Spring	117.6	105.1	-10.7	159.2	35.3
Summer	154.8	126.1	-18.5	165.5	6.9
Fall	10.2	-0.8	-108.1	13.3	30.7
Annual	284.8	231.5	-18.7	340.8	19.7

duced, and the third case used cold-soil physics. The introduction of lateral flow reduced the water available for evapotranspiration, which was de-

creased by as much as 20%. On the other hand, cold-soil processes more than offset this in wet environments. Treatment of ice appears to restrict the flow of water with the result that evapotranspiration increased by 20%.

6 Conclusion

An integrated modeling system, WATCLASS, was successfully implemented by merging a land surface scheme, CLASS, with the hydrologic model WATFLOOD. This corresponds to Level 2 modeling in the MAGS modeling strategy that would couple atmospheric and hydrologic models through a common land surface scheme. The coupled model includes the rigorous treatment of the land surfaces of CLASS, the new treatment of the soil water budget, and WATFLOOD's established routing capabilities into a powerful model that produces reasonable hydrographs over a wide range of conditions and scales. Nash coefficients increased from <0 to an acceptable range of 0.6 to 0.8 over the life of the study. Water balance closure over ten year runs were typically within 5% of the precipitation and largely independent of drainage area.

One of the by-products of the comparison is the simulation of the water-balance using six sets of forcing data from a variety of reanalysis and observation datasets. Both WATFLOOD and WATCLASS produced simulations showing an increase in water storage in the MRB over the simulation period of 1994–2004. The increase in storage was radically different between the first and second half of the simulation period. In the first half, the increase in storage was 50 mm per year for WATCLASS and 10 mm per year for WATFLOOD. For the remaining years, both models showed an average storage increase of about 2 mm per year.

Basin runoff estimates match those made by WATFLOOD but the latent heat fluxes were significantly different from those produced by CLASS. The introduction of lateral flow mechanisms reduced annual evapotranspiration for all land cover types by as much as 20%. Changes to the cold-soil physics had little impact on dry environments, but for wet environments this reduction changed to a net increase of 20%.

The work is continuing on WATFLOW. Tests include the use of significant soil horizons (i.e., the wetting front, the freezing and thawing fronts, and the water table), all of which have significant effect on water movement. Testing of a provision for transfers between separate elements to simulate the storage processes is underway, and progress is being made to streamline the calibration procedure.

Acknowledgements

The system reflects 10 years of model and database development by many researchers. The model is based on a combination of CLASS developed by Diana Verseghy and WATFLOOD developed by Nick Kouwen. Ken Snelgrove and Ted Whidden coded early versions of the model. Al Pietroniro and Murray MacKay provided institutional support. Many students' theses contributed to the algorithms. S.Z. Yirdaw provided information for Fig. 13. The construction of the drainage database relied on data from MSC, NWRI, USGS, CCRS, as well as contributions by members of MAGS.

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